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Use of phase change materials for thermal energy storage in concrete: An overview

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Abstract

The possible incorporation of phase change materials (PCMs) in building materials has attracted a lot of research interest worldwide due to the concern on global warming and the ability of PCMs to reduce energy consumption in building because of their thermal energy storage abilities. As a substance with a high heat of fusion, PCM is capable of storing and releasing large amounts of energy in the form of heat during its melting and solidifying processes at the specific transition temperature. For the past 20 years, significant research has been undertaken on the potential use of PCMs in concrete. The results showed that PCM-concrete has some useful characteristics such as better latent heat storage and thermal performance. On the other hand, PCMs have some negative impacts on the properties of concrete. However, the negative impacts can be minimized if an appropriate PCM and a suitable means of incorporation are employed during the production of the PCM-concrete. In this paper, a general review of different types of PCMs, means of their incorporation and the influence of PCMs on the properties of concrete at the fresh and hardened stages are reviewed. The stability of the PCMs, the problems in relation to using them in concrete, as well as their thermal performance in concrete are also presented.

Keywords: Phase change materials, thermal energy storage, concrete, mechanical properties, thermal properties

1. Introduction

Phase Change Materials (PCMs) are “latent” thermal storage materials possessing a large amount of heat energy stored during its phase change stage [1]. The energy required to change the phase of a substance is known as latent heat. Two types of PCMs, organic and inorganic PCMs have been used for building applications and the details of these materials are described in Section 2. Taking organic paraffin wax as the thermal storage material, heat is absorbed or released when the paraffin wax changes phase from solid to liquid or liquid to solid at a temperature of about 26°C. Most of the PCMs retain its latent heat without any changes in physical or chemical properties even after thousands of cycles.

Before 1980, PCMs were integrated into building materials for thermal energy storage applications, and much attention has been given to works concerned with the achievement and assessment of applying PCMs in gypsum wall boards, plasters, textured finishes, etc. [2-9]. Gypsum plasterboards with a heat capacity of 840 J/(kgK) and an assumed density of 905 kg/m³ and a thickness of 12.5 mm results in an overall thermal capacity of 10kJ/(m²K). It is well-known that materials with a good thermal storage capacity are typically solid and dense (e.g concrete). The relevant differences between gypsum and concrete are the specific heat capacity as well as the thermal conductivity which will eventually affect their thermal performance. If it is assumed that concrete has a heat capacity of 1000 J/(kgK), a density of 2300 kg/m³ and a thickness of 24 cm, this results in an overall thermal capacity of 552kJ/(m²K), which is 55 times the value of the gypsum plasterboard. Therefore, if concrete is chosen as a medium for PCMs it can lead to an increase in the overall energy storage capacity [10-14]. Also, concrete has excellent thermal insulation as well as good fire resistant properties. In order to prevent the risk of PCMs leakage in concrete, the selection of an appropriate PCM and incorporation technique in the concrete product is therefore important. This is because the organic PCMs can interfere with the cementitious materials if any leakage occurs, and thus can change the concrete properties. For instance, the leakage of inorganic PCMs can lead to corrosion of steel bars in a building structure.

Fig. 1 shows the temperature differences between night and day that ensure that the alternating sequence process of melting and solidifying of PCM functions as a heating and cooling system for a building. This means that during the daytime, PCM absorbs surplus heat by melting the PCM. If on the other hand in cooler nights, PCM becomes solid and the heat is released back into the environment. The same cycle repeats in the following days. As a result, concrete materials incorporating PCMs can provide a more stable temperature which ensures temperatures conducive to human thermal comfort in the buildings' internal space can be maintained.

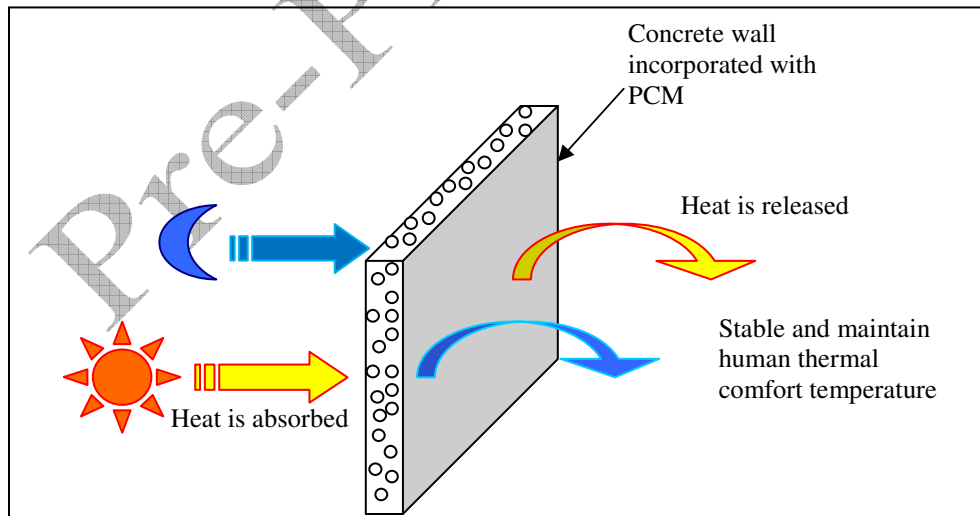


Fig. 1. Heating and cooling function of concrete wall incorporated with PCM to maintain pleasant human comfort temperature in indoor room.

The aim of this paper is to provide information on different kinds of PCMs and their specific characteristics that are suitable for incorporation into different types of concrete products. Previous works that have been conducted to study the influence of PCMs on both fresh and hardened properties of concrete are reviewed. A more comprehensive review of the effect of PCMs on the heat of hydration and thermal performance of PCM-concrete is also included.

2. Classification of phase change materials

Phase change materials (PCMs) commonly used in concrete can be generally divided into two principal types: inorganic and organic [14-15]. From a concrete design point of view, it is important to identify what kinds of PCM are suitable for use in concrete, because different kinds of PCM have different chemical natures and melting/transition temperatures. The general characteristics of inorganic and organic PCM are discussed in the following sections.

2.1. Inorganic PCM

The most common inorganic PCMs are hydrated salts (M_nH_2O) [16]. Inorganic PCM may have potential applications in some types of building materials, because of their high volumetric heat storage capacity and good thermal conductivity [17]. The added advantages are their low cost, ready availability and non-flammable nature. However, their unsuitable characteristics, such as very high volume change and supercooling during solid-liquid transition, have led to the hydrated salts not being considered as an appropriate material to be incorporated into concrete. Supercooling is a problematic issue of inorganic PCMs because the liquid state can be cooled to below its freezing point whilst remaining a liquid which makes the associated phase change ineffective. Another concern of the inorganic PCMs is their degradation and inoperative characteristic after repeated phase change cycles.

2.2. Organic PCM

Organic PCMs can be further described as paraffin and non-paraffin types [16]. Most of the organic PCMs are chemically stable, safe and non-reactive. Also, they have an ability to melt congruently without segregation and have self-nucleating properties that are compatible with traditional construction materials without posing any significant problems of supercooling.

Paraffin wax (PAR) is a hydrocarbon that has the chemical structure C_nH_{2n+2} . Commercial PAR generally has a melting point ranging from 20°C up to 70°C, depending on the number of carbon (C) atoms. The more C atoms present in the chain, the higher the melting point of the PAR. Extensive use of organic PAR with a phase change temperature of 26 °C in concrete has been successfully demonstrated by previous studies [18-21]. PAR is regarded as one of the most popular PCMs used in concrete, because it is inactive in an alkaline medium, chemically stable and inexpensive. However, PAR does have unsuitable properties such as being flammable and having a low thermal conductivity in its solid state.

The majority of organic non-paraffin PCMs are acids ($\text{CH}_3(\text{CH}_2)_{2n}\text{COOH}$). Their melting point is similar to those of paraffin PCM and they have excellent melting and freezing properties. However, they are much more expensive (about three times) than paraffin PCM. Different kinds of non-paraffin PCM have been studied to assess their suitability for use in concrete [14]. They are butyl stearate (BS), 1-Dodecanol (DD), Polyethylene glycol (PEG), 1-Tetradecanol (TD) and Dimethyl sulfoxide. Among these non-paraffin PCMs, BS seems to be the most appropriate material because of its relatively low cost, suitable melting point at human comfort temperature, high latent heat storage, low volume change during phase change transition, and inflammable and stable nature.

3. Means of PCM incorporation in concrete

There are generally a few probable means of PCM incorporation in concrete. The three predominant methods are:

- (i) Immersion [10-12]: simple immersion of the porous concrete in the melted (liquid) PCM
- (ii) Impregnation [13-14]: vacuum impregnation of the PCM in porous aggregates
- (iii) Direct mixing [15]: direct mixing of an encapsulated PCM in the concrete mix during concrete mixing stage

Previous studies have demonstrated that the means of incorporation of PCM in concrete has a marked effect on the overall thermal and mechanical properties of the PCM-concrete.

3.1. Immersion technique

The immersion technique was first introduced by Hawes [17] which involves the soaking of the porous concrete products in a melted (liquid) PCM (named immersion PCM-concrete). This technique is conducted by immersing porous concrete products in a container which is filled with the liquid PCM. The effectiveness and the time required (immersion time) for the liquid PCM to be fully soaked into the porous concrete are mainly based on three criteria: the absorption capacity of the concrete, the temperature and the types of PCM being employed. The process of immersion normally takes several hours.

Hawes and Feldman [10] investigated the effect of different types of porous concrete on the absorptivity of PCM in concrete. Their results showed that at $80^\circ\text{C} \pm 5$, the immersion time must be adequate to allow the liquid PCM to soak into the voids of the concrete blocks. Two types of concrete products, autoclaved concrete blocks and regular concrete blocks, were compared. The time required for the autoclaved concrete blocks to be fully soaked with BS and PAR varied from 40 min to 1 h, whereas the regular concrete blocks with PAR required about 6 h. This indicates that the autoclaved concrete blocks is a better choice for immersion due to its higher porosity and higher degree of absorption compared to the regular concrete blocks. The higher the temperature of the liquid PCM employed, the faster the speed of the immersion process.

Using visual and differential scanning calorimetry (DSC) analysis, Lee et al. [23] observed that good distribution of BS and PAR when immersed in both autoclaved and regular concrete blocks. Nevertheless, some of the PAR leaked out during the heating cycles resulting in a very thin film of PAR remaining on the exterior surface of the regular concrete blocks. However, this situation did not adversely affect the chemical reaction in the concrete products due to its strong chemical stability. For actual application, special treatments during the immersion of PCM-concrete products are necessary in order to prevent any melted PCM from flowing out the concrete that may otherwise contaminate the environment. Salyer [24] suggested that silica particles could be added to prevent the leakage of PCM from the concrete.

3.2. Impregnation technique

The impregnation technique involves three simple steps [15]. First, air and water are evacuated from the porous or lightweight aggregates with a vacuum pump. Then, the porous aggregates are soaked in the liquid PCM within a controlled environment (under vacuum). Finally, the pre-soaked PCM porous aggregate functioning as a “carrier for the PCM” is mixed into the concrete.

Zhang et al. [14] studied the influence of porous aggregate types on the capability to absorb PCM. Three types of porous aggregates were examined: expanded clay aggregate (C1), normal clay aggregate (C2) and expanded shale aggregate (S) as the “carrier” for butyl stearate (BS) PCM. Table 1 gives the basic properties and the results of PCM-absorption capacity for these porous aggregates. It can be seen that there is a general trend of increasing PCM-absorption capacity when the density of the porous aggregate is decreased (higher porosity). When compared to the absorption capacity for water, the vacuum impregnation method was much more effective than the simple immersion technique. The difference was more pronounced in the clay aggregate than in the shale aggregate. A rough estimation of PCM-absorption capacity for C1, C2 and S were 0.876, 0.176 and 0.081 ml/g of the porous aggregate, respectively. This indicates that PCM can occupy up to 75% of the total pore space of the C1 porous aggregate.

Bentz and Turpin [15] conducted DSC experiments to test the heat flow of lightweight aggregate soaked in PEG and PAR PCM. From the DSC analysis results, it was found that the peak temperature of PAR at melting and solidification was slightly higher than for PEG. Furthermore, soaking porous aggregates in PCM enhanced the heat transfer between the PCM in the porous aggregate and the bulk concrete.

Table 1. Basic properties and PCM-absorbing capacity in different porous aggregates (sourced from Zhang et al. [14])

Notation	Density (g/cm ³)	Porosity (%) (MIP)	Water-absorbing capacity by simple immersion (%)	Water-absorbing capacity by vacuum impregnation (%)	PCM-absorbing capacity (ml) per 1 g of porous aggregate
C1	0.76	75.6	11.0	72.5	0.876
C2	1.25	41.9	5.9	42.5	0.176
S	1.39	33.8	4.1	15.0	0.081

3.3. Direct mixing technique

Another means of incorporation of PCM is the direct mixing technique [16]. Before the PCM can be directly mixed into concrete constitutes during their mixing process, it must be first encapsulated within a chemically and physically stable shell. This is essential to retain the PCM in its pure form and ensure no interference with the concrete constitutes. Also, when the PCM is in a liquid form (during melting), the capsules ensure that none of the liquid PCM leaks out. The most common processes used to encapsulate organic PCM are interfacial polymerization [25], emulsion polymerization [26], in situ polymerization [27] as well as spray drying and coacervation [28].

For direct mixing, the surface (shell) hardness of the PCM microcapsules needs to be indestructible and sustainable to avoid any breakage (damage) during the concrete mixing and casting process. To prevent any premature rupture in these stages, membrane reinforcement products such as Zeolite or Zeocarbon (mostly derived from charcoal and volcanic rock) can be used for surface reinforcement to withstand high friction or impact [28]. Recently, an attempt was made to assess the feasibility of using different amounts of Micronal DS 5008 X (micro-encapsulated paraffin wax PCM) as the direct replacement for marble powder in the production of self-compacting concrete. The results showed that the porous micro-structures and spherical voids of the broken PCM microcapsules could be observed by scanning electron microscopy (SEM). SEM micrographs (Fig. 2a) indicated that the flaked structures of the solidified wax covered the inner wall of the pore. Upon close examination of the pore wall, a large volume of cell walls, which appeared to be smooth from the outside, could be observed. Fig. 2b shows that the predominant size of PCM microcapsules is about 6 μm which densely occupied the cement matrix.

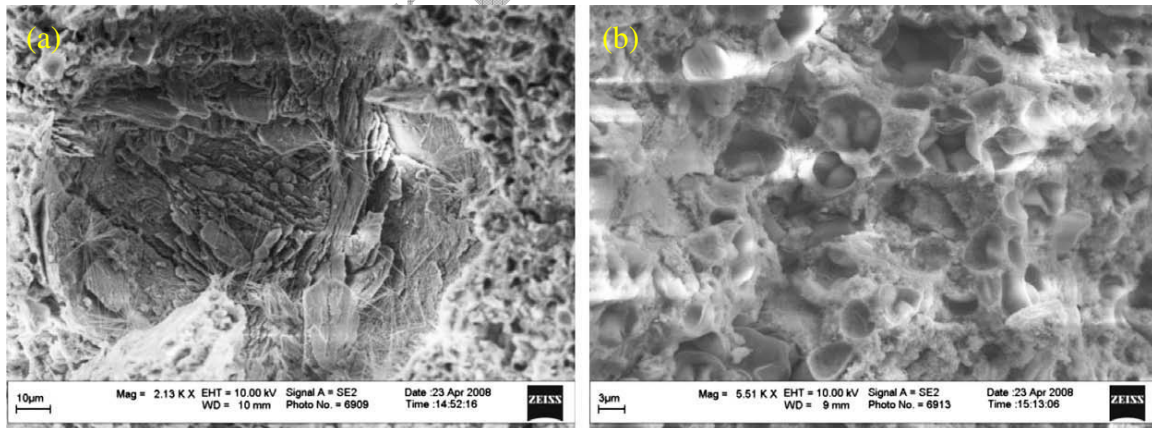


Fig. 2. SEM micrographs of (a) an open pore covered with solidified wax, and (b) a higher magnified ($\times 5500$) part of the matrix with deformed and broken microcapsules, partly pure leaked wax is visible (sourced from [16]).

4. Fresh properties of PCM-concrete

Hunger et al. [16] examined the effect of directly mixing micro-encapsulated phase change material (MCPCM) on the fresh properties of self-compacting concrete (SCC) by testing the slump flow, V-funnel time and J-ring properties. The overall results showed

that it is feasible to produce good self-compacting properties using PCM microcapsules. The flow diameters of all the PCM-SCC mixtures were similar when compared to plain SCC mix by adjusting the water content and the dosage of superplasticizer. It was found that the SCC mixtures with 3% and 5% PCM microcapsules content displayed slightly higher viscosity, which was attributed to the higher water content. It is hypothesised that the particle size of PCM microcapsules used could affect the workability of the concrete mixture [29].

5. Heat of Hydration

Bentz and Turpin [15] investigated the temperature rise and decrease during the first few days of the hydration of cement mortars at semi-adiabatic conditions. Three types of mortar were used. They were (i) a control mortar with a cement-to-nonporous coarse sand and water-to-cement ratio of 3 and 0.40, respectively; (ii) a mix containing 100% pre-impregnated lightweight aggregate with PAR as PCM; (iii) a mix containing 100% pure PAR particles as total replacement of aggregate on a volumetric basis. It was observed that the characteristic of heat evolution of PCM-mortar was strongly influenced by the presence of PCM. The use of PCM resulted in a reduction in the maximum temperature rise and the reduction was more pronounced when the PCM was directly added to the mixture. Also, using paraffin wax PCM in the cement mortar caused an one-hour delay in reaching the peak temperature which was an indication of retardation of cement hydration.

Sakulich and Bentz [30] incorporated expanded clay and porous Greek pumice aggregates with PAR, PEG, and vegetable oil-based PCM into cement mortars. They found that PAR had no effect on the hydration reaction, while the PEG and vegetable oil-based PCM had a significant effect in retarding (delay in reaching peak temperature) and suppressing (reduction in peak temperatures) the hydration of the cement matrix. For all PEG mixtures, it was found that not only the maximum heat flow decreased by about 40%, but the heat evolution had been also delayed by several hours. It suggested that the amounts of non-absorbed PCM adhering on the aggregates surface were likely to be a problem during cement hydration. Similar results for heat evolution in the case of direct mixing were also reported by Hunger et al. [16].

6. Mechanical properties

6.1. Compressive strength

The compressive strength results of PCM-concrete have been reported by several studies. The results indicate that the PCM content as well as the means of PCM incorporation in concrete noticeably affect the compressive strength of the PCM-concrete.

Investigations on using the immersion technique have found that there is no significant difference in the strength between the control and immersion PCM-concrete. Hawes [17] reported that when PAR is in the liquid state, the PCM-concrete exhibited a similar strength with that of the control concrete. However, when compared to the control concrete there was an approximately 50% increment in strength when PAR was in the solid state. Cabeza et al. [20] reported that the innovated PCM-concrete was found to achieve a compressive strength of over 25 MPa and a tensile splitting strength of over 6

MPa (after 28 days) which are appropriate levels for some structural application purposes.

However, in the case of direct mixing, inclusion of PCM microcapsules in SCC significantly reduces the compressive strength [16]. The compressive strength of PCM-SCC decreases by 13% for each additional percentage of MCPCM added by total concrete weight. The two mechanisms responsible for this decrease in strength are (i) significant disparity between the intrinsic strength of the microcapsules and other concrete constituents such as cement paste, and (ii) damage of MCPCM resulting in paraffin wax leaking from the broken microcapsules and mixing with other concrete constituents.

6.2. Concrete porosity and intrinsic concrete density

Hunger et al. [16] investigated the concrete porosity (as part of the void fraction which is open to the surface) of a control SCC and PCM-SCC mixtures prepared with 1%, 3% and 5% of MCPCM by total weight of concrete. They reported that the PCM-SCC containing MCPCM had higher porosity values than the control SCC. This might be due to the structural change of the concrete packing density. The intrinsic concrete density of the PCM-SCC decreased with an increase in the MCPCM content, probably due to the relatively low specific gravity of the MCPCM (0.915 kg/m^3) when compared to other constituents in the concrete.

7. Thermal properties

The impacts of applying PCM in concrete products on their thermal properties are well documented [10-18]. Across a number of previous studies, all the reported data showed that the heat storage capacity of concrete is significantly increased when PCM is applied. Of course, the effectiveness is dependent upon the PCM type and means of incorporation adopted during the production of the PCM-concrete.

7.1. Thermal energy storage capacity/thermal mass

Zhang et al. [14] investigated the thermal energy storage capacity of normal concrete materials, and concrete prepared with porous aggregates with and without BS PCM. According to the results from the DSC test, it was found that all the concrete containing pre-soaked BS porous aggregates had endotherm peaks ranging from 10 to 30 °C. The peak and ending temperatures of the phase change increased linearly with the PCM-absorption capacity of the porous aggregates used in the concrete.

Hunges et al. [16] studied the specific heat capacity of SCC made with various percentages of MCPCM by means of direct mixing. The prepared PCM-SCC specimens with dimensions of 200×200×30 mm were introduced in a samples holder and the temperature was maintained at 32 °C during the heating process. The specific heat capacity and thermal mass of the samples were calculated based on the temperature of the samples and the amount of heat flux from the device. The results of the specific heat capacity versus temperature of the samples containing 0%, 1%, 3% and 5% of MCPCM by mass of concrete are shown in Fig. 3. It is evident from this figure that (i) the specific heat capacity of the samples increased by up to 1.7, 3.0 and 3.5 times with the increase in

PCM replacement level by 1%, 3% and 5%, and (ii) the melting temperature of all the samples with PCM ranged from 23 to 26 °C.

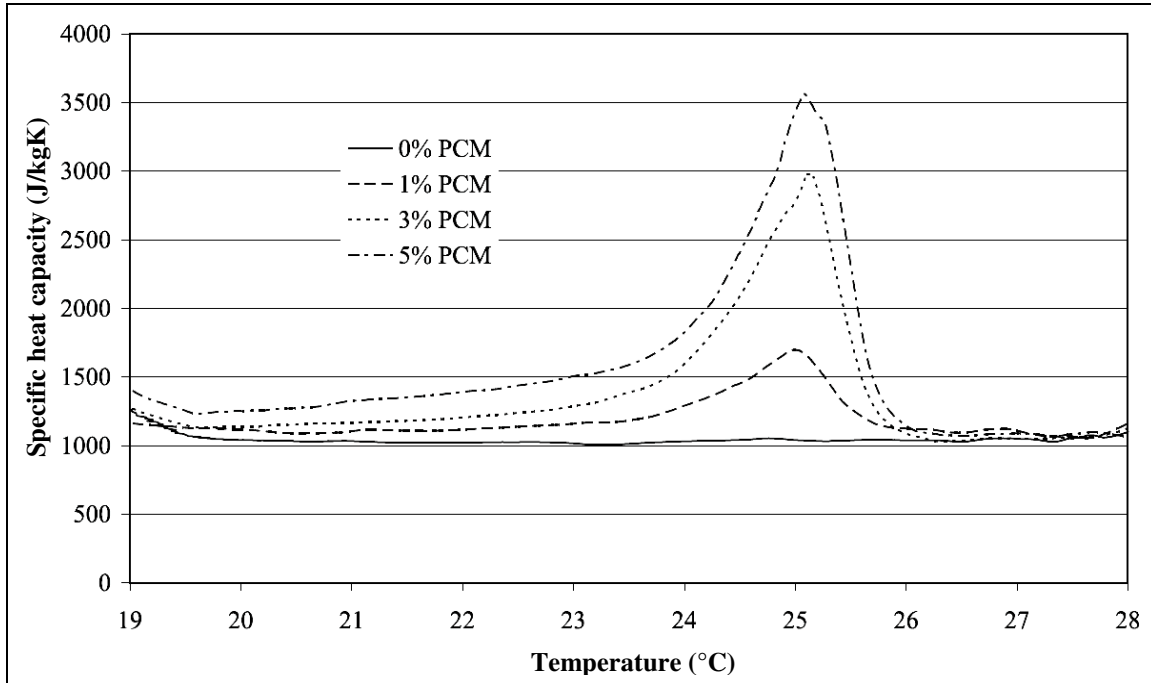


Fig.3. Specific heat capacity of the PCM-SCC mixes versus temperature (sourced from [16])

7.2. Thermal conductivity of PCM-concrete

Hunges et al. [16] examined the effect of PCM additions on the thermal conductivity of concrete. Four mixes were designed containing 0%, 1%, 3% and 5% of MCPCM. MCPCM was used to replace marble powder on a volumetric basis (similar particle size distribution). For every mix design, two samples of 100×100×50 mm were prepared for the measurement. It was found that the inclusion of MCPCM in concrete resulted in a lower thermal conductivity of concrete by linear function. The reduction is generally attributed to the enhanced air content and the lower thermal conductivity of PAR.

Hawes [17] measured the thermal conductivity of immersion autoclaved and regular concrete blocks without PCM, with BS, with DD and with PAR. The specimens with BS and DD were tested when the PCM was in the liquid state whereas the specimens with PAR were tested in the solid state. The differences of conductivity of PCM in liquid and solid states appear to be insignificant. For a given PCM type, the thermal conductivity of the regular concrete blocks was higher than that of the autoclaved concrete blocks due to their relatively higher density. In comparison, the PCM-concrete showed a steady decrease in air voids and offers a better thermal conducting path than the plain concrete without PCM.

7.3. Field investigation of PCM-concrete cubicles

Laboratory results show that the use of PCM in concrete did enhance its thermal energy storage. Extensive studies have been carried out to investigate the thermal performance in

real buildings under the EU project MOPCON with partners from Spain, the Netherlands, Greece and France [20, 31]. Prototype buildings with dimensions of 2×2×3 m were constructed by shaping cubicles of PCM-concrete fully instrumented with temperature sensors in the internal surface of each panel wall. The micro-encapsulated PAR PCM content in the concrete panels was 5% by total concrete mix weight with a melting temperature of 26 °C and a phase change enthalpy of 110 kJ/kg. The measured “outside temperature” and “internal temperature” in the west wall with and without PCM in the cubicle building is presented in Fig. 4.

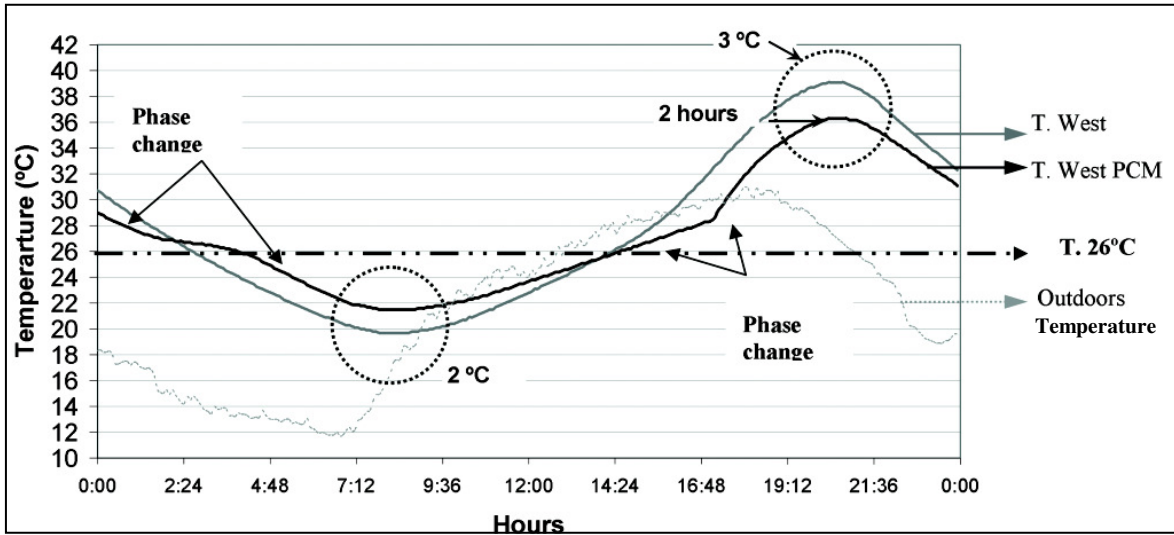


Fig. 4. Outside temperature and temperature of the west wall with and without PCM with closed windows tested in July 2005 (sourced from [31])

It is evident from this figure that with up to 24 hours of testing during a summer day, the cubicle walls with PCM always obtained a smaller temperature value (2 – 3 °C) than the cubicle walls without PCM. When the “outdoor temperature” reached the maximum of 31 °C, the west wall of the cubicles with PCM reached only 36 °C, which is 3 °C lower than that of the cubicles without PCM. It was also noted that the cubicles with PCM reached the same temperature of the cubicles without PCM about 2 hours later. This indicates an improved performance in thermal inertia as well as lower internal temperatures of the cubicles incorporated with PCM.

8. Stability of PCM in concrete

8.1. Alkalinity

One of the parameters that need to be taken into consideration when incorporating PCM in concrete is the alkalinity level of concrete. It is known that not all PCM is suitable for use in high-alkali level concrete because the alkali can degrade some PCMs. Hawes [17] investigated the alkalinity of various concrete types by determining the pH values of the water in which the concrete specimens were immersed for 28 days. The preliminary results found that autoclaved concrete blocks had the least alkali content, followed by regular concrete blocks, pumice concrete and lightweight concrete prepared with expanded shale aggregate (EXSL). He also reported that BS, DD and TD were more

suitable for use in concrete with lower alkalinities. In the case of PRA, it was quite stable in all the concrete types since it is chemically inactive in the alkaline media. This was measured by the DSC method and confirmed by chemical analysis. The worst case was the use of polyethylene glycol (PEG) PCM which tended to deteriorate in most concrete types.

Since some concrete types, like pumice concrete block, appear to have a high absorption capacity which is ideal for PCM incorporation, there is a strong need to reduce the alkali content in these concrete types. Hawes [17] proposed to use pozzolans to reduce the alkalinity of concrete. However, the amount of pozzolans used must be controlled at an appropriate level to ensure that the concrete retains sufficient porosity to absorb the required amount of PCM.

8.2. Freeze/thaw cycling

Hawes [17] compared the freeze-thaw durability of immersion PCM-concrete through the use of different types of concrete blocks and PCMs. The test was conducted with a frequency of 6 h per cycle and the temperatures were alternated between 33 °C and -25 °C for a total of 50 cycles. No significant difference was observed in the freeze-thaw performance of the autoclaved blocks (ABL) containing different kinds of PCM (BS, PAR and PEG). It was noted that the immersion PCM-concrete had better resistance to freeze-thaw cycles than that of the control specimens without PCM due to the reduced water absorbency and lower permeability.

Regarding the effect of concrete types, Lee [12] found that the loss of weight of the autoclaved concrete blocks with PAR after 20 heating and cooling cycles was much lower than that of the regular concrete blocks with PAR. For the autoclaved concrete blocks, the PCM loss was about 5% while for the regular concrete blocks it was about 31%. This is because the regular concrete block had a denser structure and most of the PAR absorbed remained in the outer part of the block. Thus, during the heating and cooling cycles, PCM leakage occurring in the regular concrete blocks was much higher than that for the autoclaved concrete blocks.

Bentz and Turpin [15] used a computer model to simulate the number of expected freeze/thaw cycles to failure of a control concrete and PCM-concrete. The results demonstrated that the presence of PCM in concrete reduced the number of cycles by about 30% on average when compared to the control concrete without PCM.

8.3. Fire resistance

PCM has been proven to be the most suitable and effective latent heat storage material for use in concrete. However, one of the drawbacks of PCM is that it may be flammable (e.g. paraffin).

Hawes [17] investigated the fire resistance of immersion PCM-concrete. For this purpose, different types of PCM-concrete products of size 200×200×30 mm were tested under a directly impinging 700 °C flame for 10 min. Based on the observations under the fire tests, it was found that there was a reduction of PCM mass and increase of the risk of

fume discharge for the PCM-concrete. The colour of the PCM-concrete surface was also affected by the flame. In comparison, the percentage mass loss of PCM of the regular concrete blocks was relatively lower than that of the autoclaved concrete blocks. This was due to the regular concrete blocks had a greater surface tension within the smaller diameter of the pore structure than that of the autoclaved concrete blocks. The amount of visible fume discharged ranged from negligible to moderate depending on the type of PCM used in the concrete.

Concrete products can become flammable if the PCM used is flammable, is not encapsulated and is directly mixed in concrete in high concentrations. Macro-encapsulation or micro-encapsulation could be possible solutions to increase the PCM-concrete resistance to fire. BASF has demonstrated that PAR PCM incorporated with a magnesium oxide-based matrix can improve its resistance to flames and fire. This material has passed the Euro-class B fire rating.

9. Conclusions

Based on the above overview of the development of the use of phase change materials in concrete, the following conclusions can be drawn.

1. The possible use of phase change materials for thermal heat storage in concrete is promising. The improvement of the thermal heat storage of PCM-concrete may make it more widely used in construction and building applications; but PCM-concrete also has some undesirable properties such as lower strength, uncertain long-term stability and low fire resistance. These undesirable properties, however, can be minimized if appropriate PCM types and means of incorporation are employed.
2. Among the PCM types, organic PCM and particularly paraffin wax PCM, seems to be one of the most suitable latent heat storage materials that can be used in concrete. The main reasons are the chemical stability, inactivity in the alkaline environment of concrete, an appropriate transition temperature of about 26 °C (human thermal comfort) and low degree of supercooling; they are also relatively inexpensive and have desirable thermal stability.
3. The test results of different means of PCM incorporation in concrete showed that:
 - Immersion: suitable for concrete with a relatively high porosity. The time required for immersion is mainly controlled by (i) the absorption capacity of the porous concrete, and (ii) the temperature of the container in which the melted (liquid) PCM is filled. Basically the immersion process takes several hours.
 - Impregnation: vacuum impregnation seems to be more effective compared to the simple immersion technique. By comparing the results of absorption behaviour of PCM in different types of porous aggregates, expanded clay or shale aggregates are the more suitable porous materials for PCM impregnation.
 - Direct mixing: encapsulation of the PCM with a chemically and physically stable shell is required before it can be directly mixed into concrete. The surface (shell) hardness of the PCM microcapsules can be reinforced by the use of Zeolite or Zeocarbon.
4. Past studies showed that it is feasible to produce self-compacting concrete prepared with PCM microcapsules as a direct replacement of marble powder.

5. The heat evolution characteristic of the concrete is strongly influenced by the presence of PCM. Generally, the inclusion of PCM retards cement hydration.
6. The results of the various studies indicate that PCM-concrete achieves compressive strength values within the range appropriate for most construction purposes. In the case of direct mixing, the strength and density are noticeably decreased as the content of PCM in the concrete increases. PCM-concrete prepared by means of immersion showed similar strength to those of the normal control mix.
7. The inclusion of PCM in concrete yields a significant improvement in the thermal performance of the concrete. This is due to the enhancement of both the thermal insulation (lower thermal conductivity) and thermal mass. Field investigations also showed that the cubicle walls with PCM had a smaller temperature range and hence improved thermal inertia.
8. Alkali in concrete can attack some PCM such as organic non-paraffin butyl stearate (BS) and tetradecanol (TD). The use of modified (low alkalinity) concrete was able to increase the stability of PCM. Also, adding pozzolans such as fly ash or silica fume can be very effective to reduce the alkali level in concrete.
9. Immersion PCM-concrete with BS, PAR and PEG had better resistance to freeze-thaw cycles due to their lower water absorbency and lower permeability.
10. Fire resistance of PCM-concrete can be enhanced if the PCM used is inflammable and is encapsulated. However, only limited data are available in this area. Therefore, further studies are needed on the fire resistance of concrete incorporating PCM.

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